Life After NIAC

PRINTABLE SPACECRAFT

NIAC Symposium
September 27,2017

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Jet Propulsion Laboratory
California Institute of Technology

Who am I?

PRINCETON UNIVERSITY

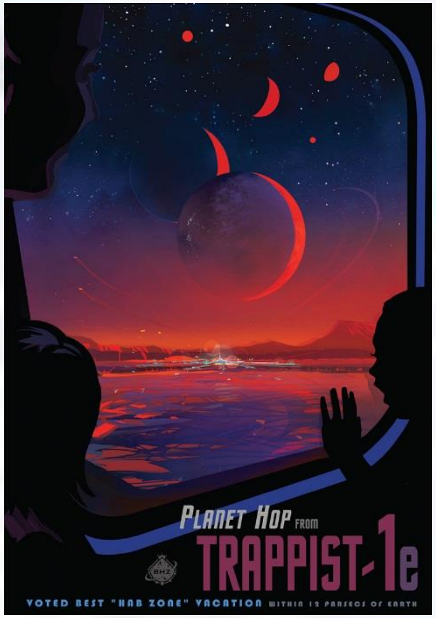
NASA

JPL

NIAC

GIRL SCOUTS

BOY SCOUTS OF AMERICA

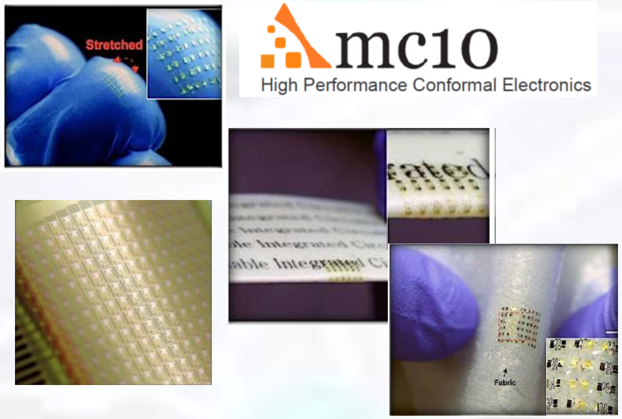


Flexible Printed Electronics

Substrates

Flexible, stretchable, dissolvable

Polyimide	Silicon	Kapton
Metallic sheet	Polymers	Ceramics
Plastics	Glass	Paper



Inks

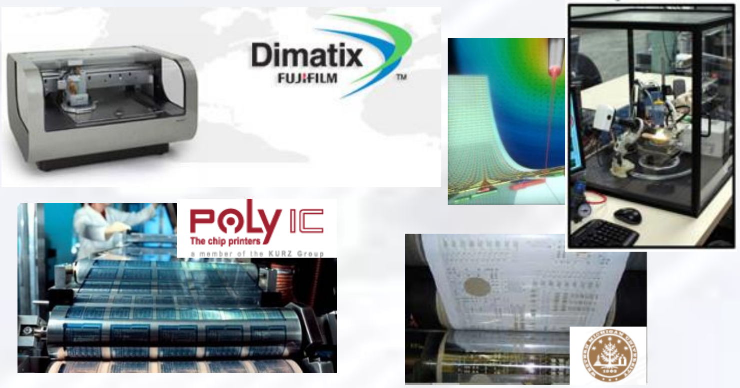
Aqueous, catalyst, CNT infused, etched

Photovoltaics	Conductors	Metals
Insulators	Semiconductors	Polymers

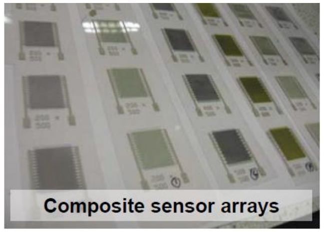
Manufacturing

High precision, sheet based, production

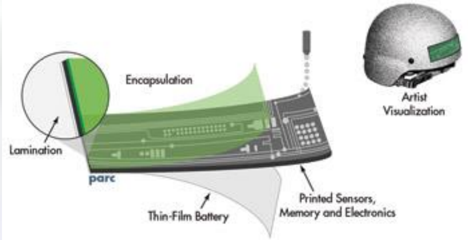
Plasma Flame	Roll to Roll	Gravure
Aerosol-jet	Ink-jet	Flexo
Screen printing	Transfer	E-jet



biomedical diagnostics institute

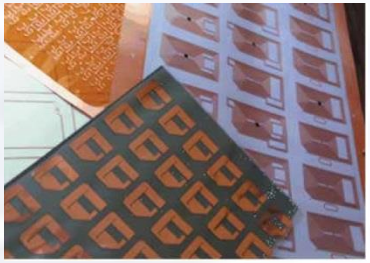


Ink-jet printed gas sensor array using polymer functionalization

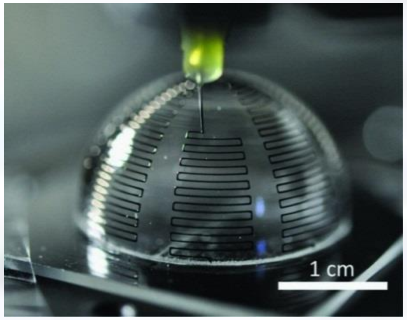


Blast dosimeters, printed with electronic sensors, memory processors and thin-film batteries. (made for DoD by PARC)

SENSORS

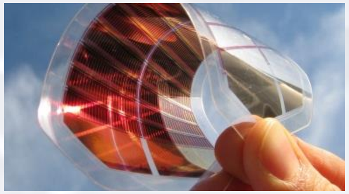


Typical flexible printed antenna



Uofl researchers develop nanoparticle inks to print 3D antennas

ANTENNAS



Flexible Organic Photovoltaic cell (Source: Fraunhofer ISE)

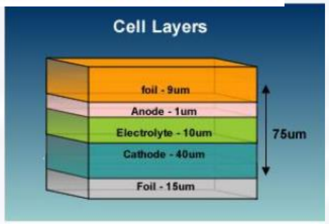
PLEXTRONICS Light. Power. Circuitry.™

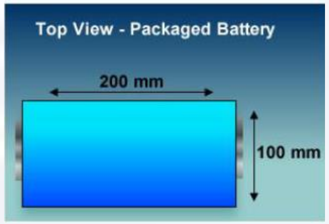
Slot-die coating of Plexcore™ photo-voltaic ink system on a 500mm R2R line

PHOTOVOLTAIC

The printed, flexible and ecologicalSoftBattery®

PLANAR ENERGY

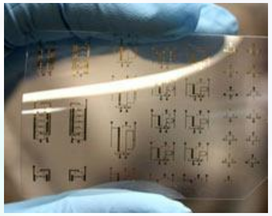


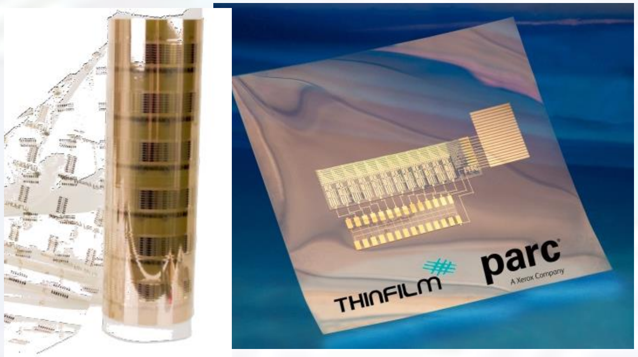


Thick film R2R deposition of solid state battery

BATTERY

These flexible carbon nanotube integrated circuits are the fastest low-power transistor arrays ever fabricated using a printer.



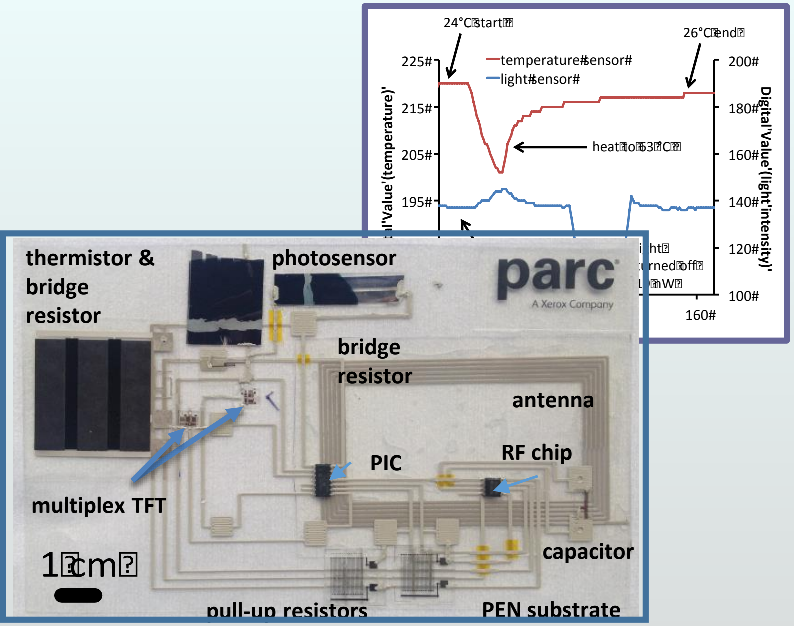


The world's first printed non-volatile memory device addressed with complementary organic circuits, the organic equivalent of CMOS circuitry

MEMORY/LOGIC

Printable Spacecraft: Flexible Electronic Platforms for NASA Missions

Kendra Short, Principal Investigator, JPL

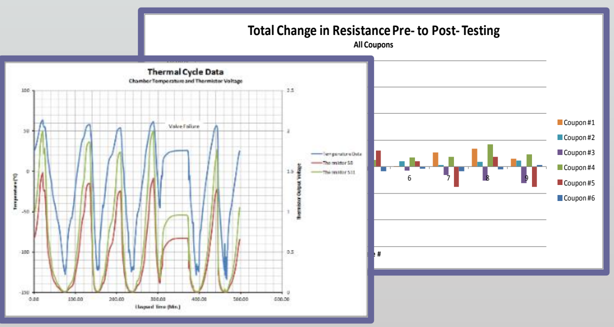


Bench-top Prototype – Printed Sensor Platform

Successfully designed and fabricated a prototype of an end to end integrated sensor system. Demonstrated two independent measurements (temperature and light intensity), the ability to multiplex the signals using low voltage TFTs, printed interconnects, integration of discreet chips for processing/ADC/RF using flexible conductive adhesive and wireless transmission of data through printed antenna.

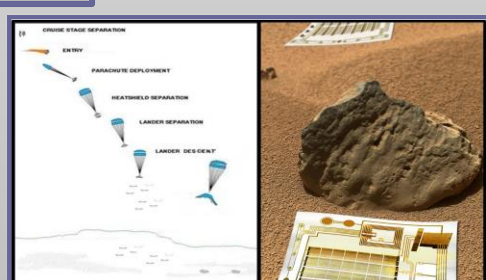
Environmental Testing – materials and device samples

Exposed substrate/ink material coupons and device samples to representative space environments. Characterized properties before and after exposure. No appreciable change in materials properties, electrical conductivity, or performance after exposure.



All Samples → **Vacuum Exposure (hard vacuum)** → **Thermal Cycle/Soak (-120 to +50 deg C)** → **Radiation (10-50 krad)** →

Baseline Test — Test Properties, Visual Inspection — Test Properties, Visual Inspection — Test Properties, Visual Inspect., Funct. Test

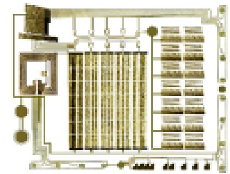


Programmatic Assessment – reference mission concept

- Defined a Mars environmental reference mission utilizing sheet-based printed flutter landers.
- Completed platform point design of printed flutter lander.
- Compared mass, cost and risk against traditional implementation.
- Prepared roadmaps towards implementation.

- Designed a “Reference Mission” application using printed Flutter Landers.
- Used as basis for cost/benefit analysis, to guide prototype design, set environmental test ranges, establish a roadmap

STANLE: Structure of the Atmosphere - Network Lander Experiment



A novel flat sheet flutter lander made from flexible electronics –requires no landing hardware - creates a thousand node environmental network

Mission Objectives

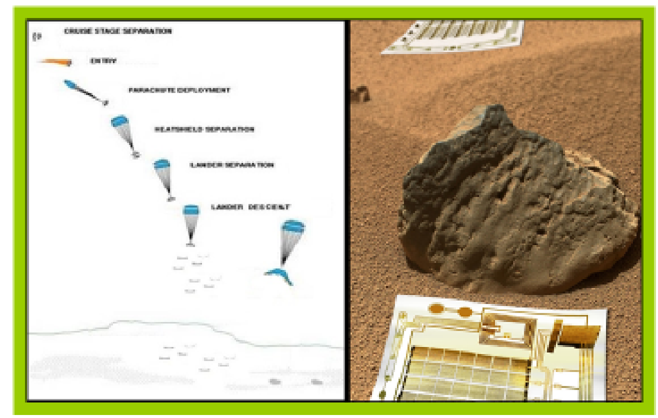
The STANLE mission will deliver thousands of environmental science platforms to the surface of Mars. Dispersed over large areas these meteorological stations will create a high density sensing network, measuring critical environmental parameters once every hour for a year.

This revolutionary new scientific platform – a printed spacecraft - is a thin flexible sheet with printed flexible electronic circuits to provide all functions from sensing to data downlink.

This novel science station provides power via solar cells and batteries. It can store up to five days worth of data from each sensor on board. When interrogated by a relay orbiter, the station downloads its data via UHF link.

Lander Technical Facts

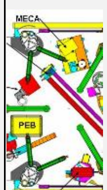
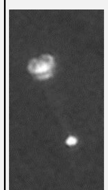
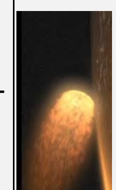
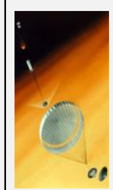
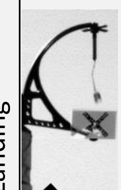
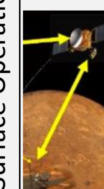
- Weight less than 13 grams
- Sheet thickness ~125 μm.
- Sheet area 25 x 25 mm
- 10 kbits of data storage
- 8 bit A/D conversion.
- 35 mAhr rechargeable battery.
- 100 mW solar cell.
- UHF data link to relay satellite.
- Six meteorological sensors:
  - Atmospheric temperature
  - Surface pressure
  - Wind speed
  - Light Intensity
  - Humidity
  - Radiation



Flight System Architecture

The STANLE flight system architecture consists of a cruise stage, which is jettisoned before entry, and an aeroshell which houses the landers and dispensers. After parachute release and heatshield separation, the landers are ejected from the backshell and flutter to the surface with no additional descent or landing infrastructure. The flutter lander enables a very simple, low risk EDL mission, reducing cost and mass from that of traditional landers.

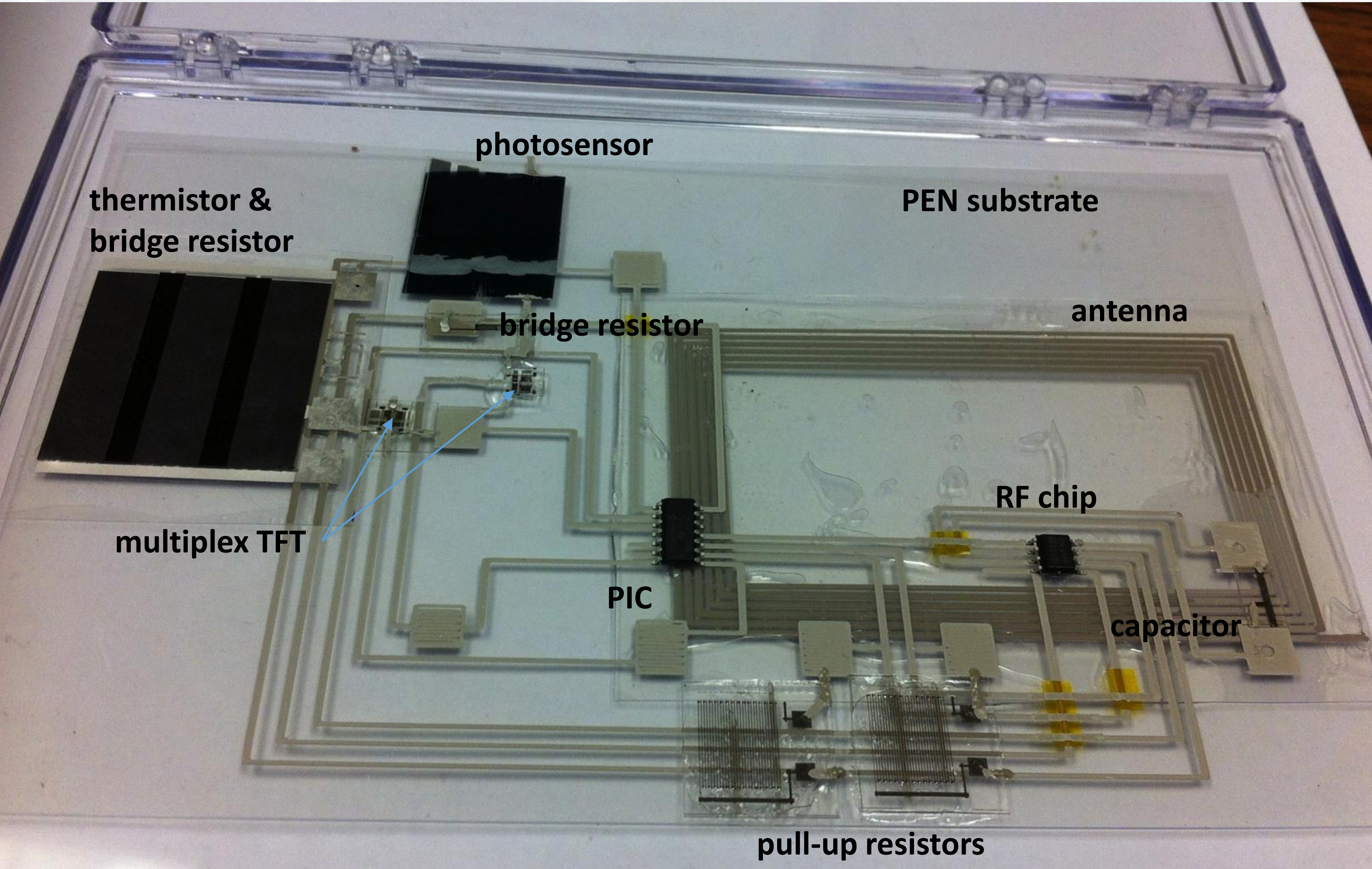
Scorecard: Printed vs Traditional

	 Payload Hardware Development	 CS /EV Hardware Development	 Descent and Landing HW Dev.	 System I&T	 Launch Operations	 Cruise Operations	 Entry Phase thru HS separation	 Descent and Release	 Landing	 Surface Operations	 Telecom Support Assets
Mass	P	Was S Now T	P ✓	NA	S	NA	S	P ✓	P ✓	NA	NA
Cost	P		P ✓	P ✓	S	S	S	P ✓	P ✓	P	?
Schedule	P		P ✓	P ✓	S	S	NA	NA	NA	Was P Now T	NA
Risk	T	S	P ✓	T	S	S	S	P ✓	P ✓	T ✓	T

Printed | Traditional | Same | ✓ *Confirmed through Team X*

Team X Study validated and quantified the "scorecard"

Printable Spacecraft Complete System - Version 2



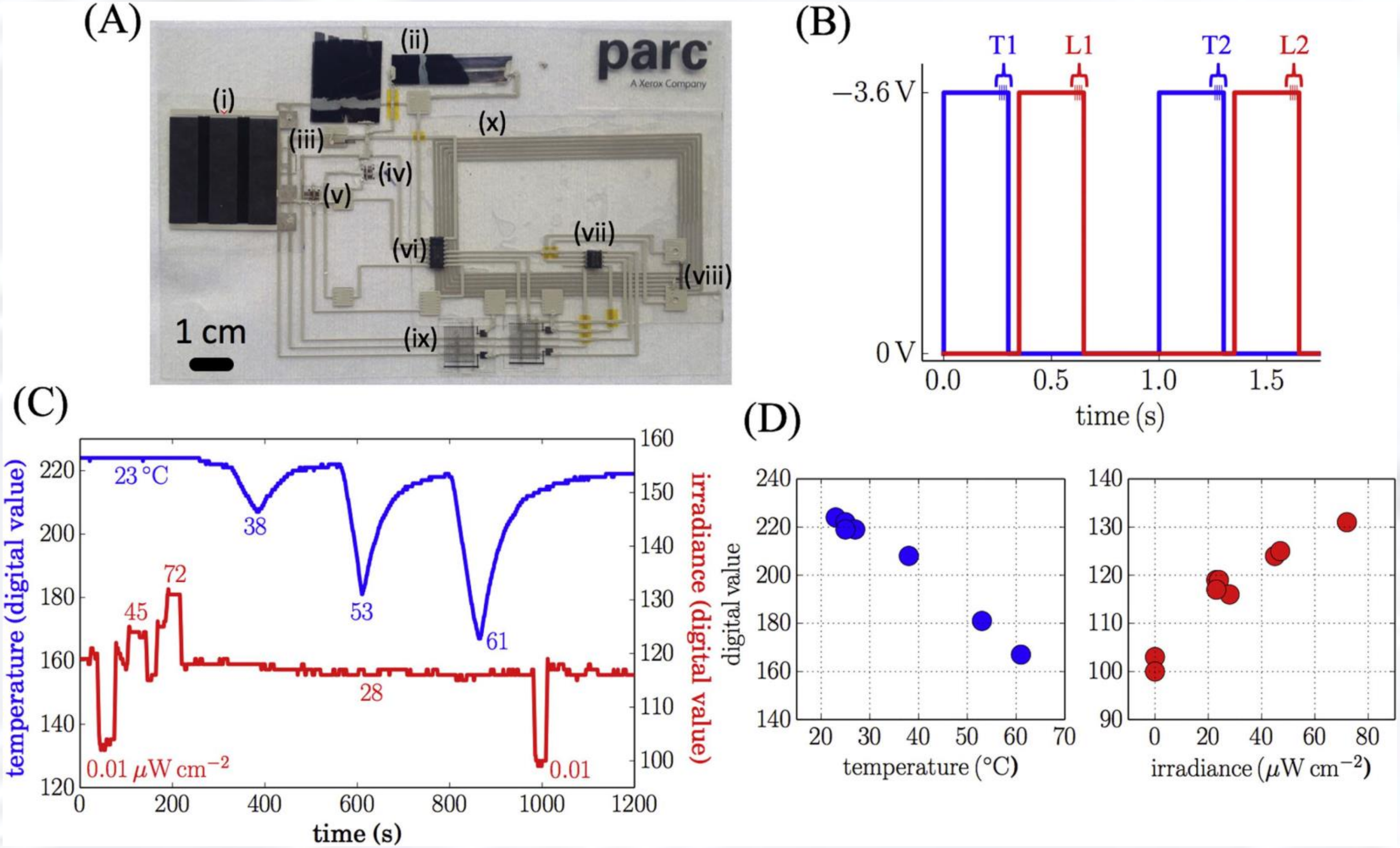


Figure 4. Complete sensor system. (A) Optical image of device with the various components annotated (i) thermistor and static resistor for temperature sensor bridge (RT and RBT) (ii) photodiode (DPh) (iii) static resistor for photodiode bridge (RBPh) (iv) photodiode multiplexing TFT (M2) (v) thermistor multiplexing TFT (M1) (vi) PIC (vii) RF IC (viii) antenna capacitor (Cant) (ix) pullup resistors, antenna. (B) Gating signals for the multiplexing TFTs for the temperature sensor (blue line) and the photosensor (red line) T1&T2 indicate the 1st and 2nd measurements taken from the temperature sensor and L1&L2 indicate the 1st and 2nd measurements taken from the photosensor. (C) Irradiance (500 nmlight, red line) and temperature (blue line) data taken from sensor system. (D) Calibration data for temperature (blue points) and irradiance (500 nmlight, red points).

- G L Whiting *et al* 2017 *Flex. Print. Electron.* **2** 034002

Environmental Test Program

All Samples → Vacuum Exposure (hard vacuum) → Thermal Cycle/Soak (-120 to +50 deg C) → Radiation (10-50 krad) →

Baseline Test

Test Properties
Visual Inspection

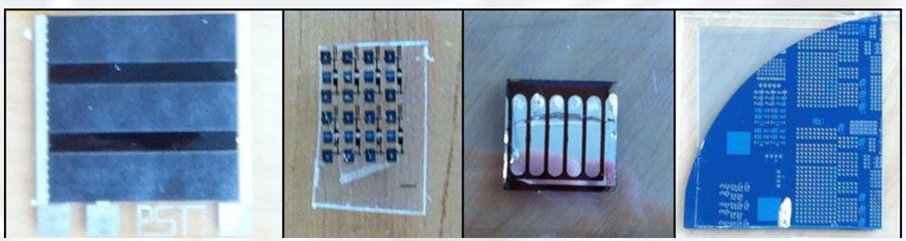
Test Properties
Visual Inspection

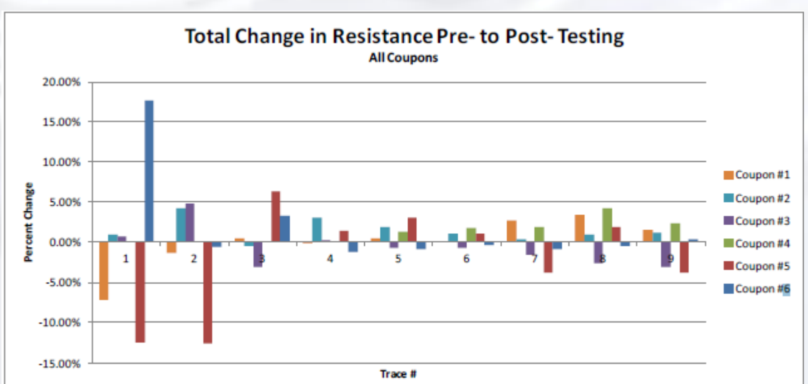
Test Properties
Visual Inspect.
Funct. Test

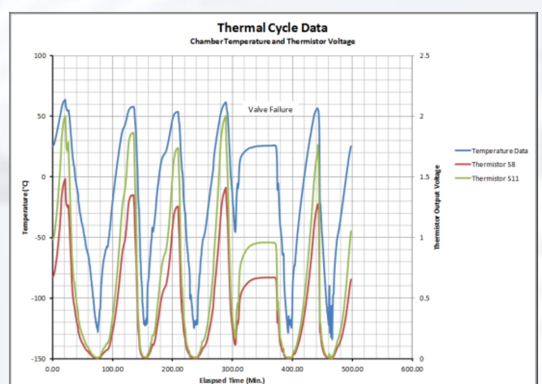
Engineering, Operations & Technology
Boeing Research and Technology

Coupon #	Substrate	Ink
#1	PEN 250µm thick	Methode 9104 (Ag)
#2	PEN 250µm thick	Methode 3804 (Carbon)
#3	PEEK 200µm thick	Methode 9104 (Ag)
#4	PEEK 200µm thick	Methode 3804 (Carbon)
#5	Kapton 125µm thick	Methode 9104 (Ag)
#6	Kapton 125µm thick	Methode 3804 (Carbon)

- Very little change before to after in resistance, performance, stiffness of material samples and functional devices.
- Some delamination of traces and solder pads.







Printable Spacecraft

JPL

parc
A Xerox Company

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BOEING
Engineering, Operations & Technology
Boeing Research and Technology

PRINCETON UNIVERSITY

Post NIAC Proposals

WIN	LOSE
"Printed Ground Penetrating Radar – Feasibility assessment" Dr Sam Kim, JPL JPL Internal funding ($30K)	Print-a-Sat – On orbit assembly and deployment of 3D and 2D printed systems NASA Ames NASA - Game Changing
"Materials and Electronic/Electromagnetic Device Development for NASA Printable Spacecraft" Dr. Whites, SDSMT NASA EPSCOR funding ($750K)	Development Roadmap and Investment Strategy for Printed and Flexible Electronics Dr. Sergio Pellegrino, Caltech Center Innovation Fund
"Fundamental Research Towards A Printable Spacecraft" Dr. Crawford, SDSMT SD RIG funding, ($750K)	Flight Demonstration of a Printed Electronic Sensor System Kendra Short, JPL ESTO Quarterly Call
"Characterization of Printed Components Under Space Conditions" Ian Markon, SDMST NASA Space Technology Research Fellow	Generation 2 Printable Spacecraft Kendra Short, JPL JPL Topical R&TD
"Digital Fabrication of Flexible Large-Area Hybrid Sensing Systems" Dr. Greg Whiting, PARC FlexTech Alliance funding ($400K)	Origami Folded – Printed solar panel Brian Trease, JPL Center Innovation Fund
STANLE Sounding Rocket Demo Northwest Nazarene University JPL Internal Funding ($30K) + NASA RockSat-X	

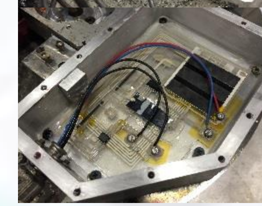
Supporting/Consulting activities

- Consulted with JPL program managers and Excelis seeking advice on additive manufacturing directions/ benefits/ investments.
- A-Team participant – workshops for 2D and 3D printed, including brainstorming with Made in Space.
- Presented short course at KISS workshop on 2D&3D additive manufacturing.
- Participant in CalTech KISS workshop on Micro-climates led by Marco Quadrelli and Adrian Stoica.
- Consulted with National Academy of Engineering representatives for their report on additive manufacturing
- SME on Flexible Hybrid Electronics IMI RFI team for DOD/Airforce.
    - Selected and established – see www.nextflex.usa

EPSCOR: *"Development of Direct-Write Materials, and Electronic and Electromagnetic Devices for NASA Printable Spacecraft" -- Dr. Dimitris Anagnostou*

NSTRF 2014: "Characterization of Printed Components Under Space Conditions" – Dr. Ian Markon

RockSat X Program



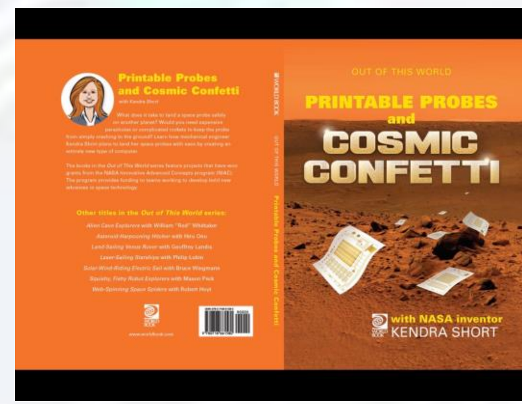
Sounding Rocket demonstration of flexible printed electronics.

Printable Spacecraft was flow as a secondary payload on the student vehicle.

Department of Defense-led Flexible Hybrid Electronics Manufacturing Innovation Institute

SAN JOSE, Calif., Aug. 24, 2016 - One year after Secretary of Defense Ashton Carter announced a $75-million award to advance the manufacturing ecosystem and workforce for flexible hybrid electronics (FHE) in the United States, NextFlex will commemorate the official opening of its manufacturing facility in San Jose

I supported as the NASA representative on the DOD team which lead to the selection of FHE as the next DOD IMI and issuance of the RFP.



STEM Education: Out of This World -- "This exclusive series was developed through World Book's collaboration with the NASA - National Aeronautics and Space Administration Innovative Advanced Concepts (NIAC) program". Ages 10-14

Xerox PARC Team
Greg Whiting
David Schwartz
Tina Ng
Janos Verdes

Boeing Team
Jeff Duce

Princeton Team
Margaret Tam
Kathleen Riesing
Professor Stengel

JPL Team
Kendra Short
Dave Van Buren

CalTech Team
Sergio Pellegrino
John Steeves
Yamuna Phal